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A review of the suitability of eucalypts for short rotation forestry for energy in the UK.

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Abstract

Eucalyptus has been identified as a genus with potential for short rotation forestry in the UK. This article assesses the suitability of *Eucalyptus* for biomass production. The first part of the article compares *Eucalyptus nitens* and *Eucalyptus gunnii* against short rotation forestry (SRF) species proposed by Hardcastle (2006), while the second part discusses limitations to the growing of eucalypts in the UK and how they may be overcome.

Eucalypts compare favourably with other tree species in the UK in terms of rapid growth (up to $30 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$) over short rotations of ten to fifteen years. The only genus that is potentially as productive in the UK is *Nothofagus*. Furthermore, most species will readily coppice, enabling regeneration after damage and avoiding the costs of replanting. The wood characteristics compare positively with other SRF species, exhibiting a moderate wood density, but limitations are a relatively high moisture and chlorine content. Many of the SRF species listed in Hardcastle (2006) are now damaged or under threat from damage by exotic pests or diseases. Eucalypts are currently relatively free from such damage.

It is cold temperatures that most limits the use of eucalypts in the UK. Eucalypts, particularly when young are vulnerable to damage from cold weather events, particularly when temperatures drop rapidly. However, the risk can be reduced by planting appropriate species and provenances, facilitating rapid growth as smaller trees are more vulnerable and by focusing on species that coppice following damage.

Key words:

Eucalyptus, United Kingdom, short rotation forestry, biomass

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Introduction

In the United Kingdom (UK) there are two main aims of the Government's Renewable Energy Strategy (DECC 2012); to reduce emissions of carbon dioxide and to improve energy security. This is to be achieved through producing 15% of the energy in the UK through renewable means by 2020, which represents an increase of seven times the 2009 contribution within a decade (DECC 2012). The lead scenario generated within the Strategy suggests that 30% of electricity and 12% of heat could be provided through use of renewable sources of energy (DECC 2012). By 2014, 7% of energy was derived from renewable sources, of which 72% was obtained from bioenergy (DECC 2015). Of this approximately 40% was from wood or other plant biomass (DECC 2015). The transition from fossil fuels to renewable sources of energy has been supported by the Renewable Heat Incentive (RHI) and the Feed-In Tariff (FIT). The RHI is focussed on providing payments to encourage the production of heat from renewable energy sources (OFGEM 2019a), while the FIT is aimed at increasing renewable electricity generation (OFGEM 2019b). The FIT scheme is closing to most applications in April 2019 but the RHI continues.

1 As a source of renewable energy, biomass has certain attractions; it can produce energy at
2 times of peak demand, it involves low fossil fuel inputs for production and tried and tested
3 technology is available for its efficient conversion. The UK Bioenergy Strategy (DECC
4 2012) predicted that while biomass imports will form the bulk of supply, domestic production
5 can provide an important, stable and reliable resource. If demand for biomass were to be met
6 domestically, the area under energy crops would need to increase dramatically. The UK
7 Biomass Strategy (DEFRA 2007) anticipated that 350,000 ha of perennial energy crops
8 would be required by 2020, which contrasts with the 2009 area of 15,500 ha of Short
9 Rotation Coppice (SRC) and *Miscanthus* (SAC 2009). Woody biomass is an attractive option
10 compared with agricultural biomass crops as it requires the input of relatively low levels of
11 fertiliser, pesticides and herbicides and can also be established on marginal land, thereby not
12 competing with food production (Hastings et al. 2014).

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30 Two approaches to bio-energy production using tree species have been adopted: short
31 rotation coppice (SRC) and short rotation forestry (SRF) (Read et al. 2009). These two
32 approaches are compared in Table 1. Since the 1990s the development of dedicated woody
33 energy crops in the UK has focused on using SRC of clones of willow (*Salix* spp.) or poplar
34 (*Populus* spp.). However, a comparative analysis of both systems identified SRF using fast
35 growing tree species as being the most cost-effective and time-efficient approach to reducing
36 greenhouse gases (Matthews and Broadmeadow 2009). However, there are very few
37 examples of SRF in the UK, with the largest plantation an area of 24.2 ha of eucalypts
38 established at Daneshill in Nottinghamshire, eastern England as an energy forest (Wooddisse
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¹ pers comm). SRF contrasts with conventional production forestry in several ways.

Conventional production forestry uses conifers, which are more productive than broadleaves

¹ Land Management Officer, Nottinghamshire City Council

1 in the UK over traditional rotations of 40-70 years. Normally SRF does not include thinning
2 during the rotation, whereas after canopy closure production forestry stands are thinned on a
3 cycle of 5 -10 years. Due to the short rotation, measures are taken to accelerate establishment
4 and maximise growth such as highly intensive weed control and fertiliser application (Purse
5 and Leslie 2016b).
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11 The silvicultural attributes of an ideal SRF tree crop are described in Table 2. Ideally it
12 should grow rapidly, with mean annual increment peaking early, have a low environmental
13 impact and the wood should have ideal properties of a fuel, such as low moisture content and
14 appropriate chemical composition. A review by Hardcastle (2006) identified species and
15 genera with potential for SRF in the UK, these being ash (*Fraxinus excelsior*), alder (*Alnus*
16 *glutinosa*), birch (*Betula pendula*), *Eucalyptus gunnii*, *Eucalyptus nitens*, *Nothofagus* spp,
17 poplar (*Populus* spp.) and sycamore (*Acer pseudoplatanus*). Of these ash, alder, birch and
18 some poplars are tree species native to the UK. Since the publication of Hardcastle's (2006)
19 report, the introduction of exotic pathogens has reduced the viability of some species, e.g. ash
20 dieback (*Hymenoscyphus fraxineus*) on ash (Thomas 2016).
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38 In the UK there has been research to identify site suitability criteria for eucalypts through an
39 understanding of the limitations to survival and growth (e.g. Evans 1980, Evans 1986, Purse
40 and Richardson 2001, Leslie et al. 2011, Leslie et al. 2012). However, the scale of planting
41 of eucalypts in the UK has been modest; in the five years between 2011 and 2016 nurseries in
42 the UK have sold about 220,000 seedlings (Purse and Leslie 2016b), which represents less
43 than 100 ha of establishment. As such, there remains uncertainty about the risks of large-
44 scale planting of *Eucalyptus* SRF in the UK.
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56 In this review paper, we compare eucalypts with other appropriate species or genera as a
57 source of biomass for energy production then identify the limitations of eucalypts in the UK
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1 and potential ways in which they may be overcome. There was found to be limited literature
2 on short rotation forestry in general in the UK. The review has therefore relied on compiling
3 information from two sources. The first is literature on cold-tolerant eucalypts that has been
4 collected by the authors over a period of fifteen years and includes material no longer on-line.
5 The information on other species, has relied on extracting relevant material from publications
6 covering more general aspects of the silviculture, growth and wood properties of the tree
7 species. A constraint to comparing growth of SRF species is that there were few data for trees
8 grown under intensive short rotation management in the UK. Whilst yield models have been
9 developed for commercial stands under longer rotations these only provide estimates of stand
10 growth after canopy closure (from 10 to 25 years of age) depending on the maximum mean
11 annual increment (Edwards and Christie 1981).
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27 This review is timely as recent research studies (eg Harrison 2011, Leslie et al. 2014b,
28 McEvoy 2016, Leslie et al. 2018) and reviews (eg McKay 2011, Leslie et al. 2012, Purse and
29 Leslie 2016a, Purse and Leslie 2016b) have led to a better understanding of the potential of
30 eucalypts but also their limitations. The findings are focused on the UK, but are relevant to
31 other areas with cool oceanic temperate climates in western Europe.
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44 ***Yield of eucalypts and other SRF species***

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50 The main attraction of eucalypts is their high productivity, being among the most productive
51 trees in the UK. Volume growth rates have been estimated from small plot trials, to be as
52 high as 30 m³ ha⁻¹ y⁻¹ for *E. nitens* (Purse and Richardson 2001). In Ireland a plantation of *E.*
53 *nitens* felled at 16 years of age, with 740 stems ha⁻¹, yielded a mean annual increment (MAI)
54 of 26.1 m³ ha⁻¹ y⁻¹ (Hutchinson et al. 2011). Historic Forestry Commission data provides
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evidence of MAIs of $16 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ for *E. gunnii* over a twenty year rotation (Leslie et al. 2018). Purse and Richardson (2001) conclude that higher yields of 10-15 oven dry Mg $\text{ha}^{-1} \text{ y}^{-1}$ (approximately $20\text{-}30 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$) over 8 to 10 year rotations are possible from plantations of *E. gunnii*. In Redmarley, Gloucestershire in the south of England (Figure 1), *E. gunnii* was estimated to have grown at a MAI of $25 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ over a 11 or 12 year rotation (Purse and Richardson 2001). The coppice from this stand was assessed at 10 years of age and the standing volume of mainly *E. gunnii* with some *E. dalrympleana* combined was $317 \text{ m}^3 \text{ ha}^{-1}$ or $31.7 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ with 4,746 stems ha^{-1} (McKay 2010). Furthermore, when *E. gunnii* and *E. nitens* that had been damaged or killed by extreme cold in the winter of 2010-2011 was harvested at Daneshill in Nottinghamshire in the north of England (Figure 1) at 5 years old an average of 85 Mg were extracted per hectare giving a green weight production of $17 \text{ Mg ha}^{-1} \text{ y}^{-1}$ (Wooddisse pers comm).

While eucalypts can be highly productive in the UK yields vary considerably across sites due to edaphic and climatic conditions, the quality of silvicultural practices and the genotype of the planting stock (Kerr and Evans 2011). This was highlighted by a study of four trials from the 1980s that demonstrated the difficulties in consistently achieving high levels of productivity (Kerr and Evans 2011). It was only at one trial at the New Forest (Figure 1), in southern England where the potential of fast growth of eucalypts was realised; biomass at seven years of age of *E. gunnii* and *E. glaucescens* was at least three times that of the other species planted, which were *Alnus cordata*, *Nothofagus obliqua*, *Populus balsamifera* and *Pteryocarya x rehderiana*. This trial was planted at two spacings and the results showed that increasing stocking significantly increased yield over a seven year rotation. For *E. gunnii* a MAI of $2.7 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ was achieved at 2.8 m spacing and of $13.9 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ at 1.4 m spacing. For *E. glaucescens* the respective MAI was $8.1 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ and $17.4 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$.

SRF species should exhibit a peak in mean annual increment (MAI) at a relatively young age.

The potentially most productive genus other than *Eucalyptus* is *Nothofagus* and UK yield models predict maximum mean annual increments (MMAI) of 10 to 18 m³ ha⁻¹ y⁻¹ (Tuley 1980). The mid MMAI of this range for *Nothofagus* shows MAI peaking at 14.0 m³ ha⁻¹ y⁻¹ at 29 years of age (Tuley 1980). Poplars have been used in short rotation coppice due to their rapid early growth (Mitchell et al. 1993) and have been predicted to produce yields of 30.5 m³ ha⁻¹ y⁻¹ or 22 Mg ha⁻¹ y⁻¹ (at 35% moisture content) at age 15 years (Forest Research 1997). Stokes et al. (2017) has demonstrated the fast growth of hybrid aspen (*Populus x wettsteinii*) and commercial hybrid poplar clones in two Scottish trials at Moray and Kilmichael (Figure 1). An assessment was made after 22 growing seasons at Moray and 21 growing seasons at Kilmichael. Clones of commercial poplar hybrids attained an average height of 19.98 m and 14.15 m respectively and a diameter at breast height (dbh) of 39.98 cm and 24.29 cm. Hybrid aspen exhibited more rapid growth with a height of 17.38 m and dbh of 30.99 cm at Kilmichael. Native aspen (*Populus tremula*) grew more slowly, achieving a height of 10.75 m and dbh of 14.97 cm at Moray and a height of 6.54m and dbh of 8.86 cm at Kilmichael.

A review of the silviculture of alder across Europe showed that current annual increment (CAI) peaks at 20 years and MAI at between 30 and 50 years (Claessens et al. 2010). In Europe sycamore also exhibits an early peak in CAI and MAI and it is described as growing more rapidly than beech (*Fagus sylvatica*) up to an age of around 40 years and as being more productive than ash, on both poor and fertile sites (Hein et al. 2009). In most European countries birch is slower growing than sycamore or ash (Hynynen et al. 2009). The mean and range of MMAI and biomass productivity for these SRF species are presented in Table 3, while biomass productivity is based on SRF rotations, the MAI of species other than the eucalypts is based on conventional silviculture and rotations.

Wood properties and important physiological and morphological characteristics

There are physiological, morphological and wood characteristics that are attractive in a SRF species. The first is the ability to coppice (Dickman 2006, Hinchee et al. 2009, Guidi et al. 2013), as it avoids the costs of replanting and results in enhanced growth rates in the second and subsequent rotations (Pukkala and Pohjonen 1990). All tree species described in Hardcastle (2006) will coppice or sucker, except for *E. nitens* which has a very limited ability to coppice (Neilan and Thompson 2008). While birch coppices after cutting it only does so weakly and so this not a recommended means of regenerating stands (Cameron 1996). For eucalypts the ability to coppice also confers a degree of resilience to damage. During the winter of 2010-11 stems and foliage of *E. gunnii* were killed at a planting at Daneshill, Nottinghamshire in the north of England, however many of the trees later produced coppice shoots and remain healthy to this date, whereas trees of *E. nitens* were killed. This supports the recommendation that in the UK, only species that coppice, such as *E. glaucescens*, *E. gunnii* and *E. rodwayi* (Sims et al. 2009) should be planted, rather than the few species like *E. nitens* that do not have this capability (Neilan and Thompson 2008).

For wood used for solid fuel, rather than conversion into liquid fuels, the main factors determining its suitability are moisture content, heating value, proportion of fixed carbon and volatiles, the ash content and the alkali metal content (McKendry 2002). Moisture content strongly affects the net heating value of wood when it is burned (Huhtinen 2006). There is considerable variation in moisture content between the tree species selected by Hardcastle (2006) (Table 3). Eucalypts have relatively high wood moisture content and experience in Ireland has shown that drying *E. gunnii* can be problematic. The wood only dried rapidly when the bark was removed and this itself was difficult using machinery because of its

1 fibrous nature (Leslie 2013). The heating value of dry wood of different tree species varies
2 relatively little with conifers having a higher value per unit of dry wood than broadleaves,
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4 due to higher lignin content and the presence of resins (McKendry 2002). However, wood
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6 density varies considerably between the tree species. Dense wood is an attractive trait for
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8 fuelwood (Senelwa and Sims 1999), as higher densities represent a higher mass of material
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10 and therefore energy per unit volume and allows a higher mass of wood to be transported per
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12 unit volume. Alder and poplar exhibit a low wood density, the eucalypts and *Nothofagus*
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14 moderate density and sycamore, ash and birch exhibit higher density wood (Table 3).
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20 Many of the species have not been burned for energy on an industrial scale in contrast to
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22 short rotation coppice. Ash, is known to produce good domestic fuel wood (Savill 2013)
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24 while in Sweden, birch is widely used as a source of domestic heat (Hedberg et al. 2002). A
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26 study of the effects of torrefaction, a heating process that improved the quality of wood fuel
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28 in terms of combustion and gasification on wood from trees including birch, aspen and
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30 eucalypts showed that the two eucalypt species tested contained chlorine concentrations eight
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32 times that of aspen and six times that of birch (Keipi et al. 2014). Chlorine can be corrosive
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34 to boilers and pipework in power plants. High levels of chlorine have also been reported
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36 from eucalypts grown in Ireland (Teagasc 2015).
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43 A regular, straight stem enables more efficient handling, storage and processing (Walker et
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45 al. 2013), although if the material is to be chipped on site when harvested this is less
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47 important. Potential SRF species known to exhibit good stem form include *E. nitens* (Neilan
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49 and Thompson 2008), *Populus* (Savill 2013) and silver birch (Hynynen et al 2009), while the
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51 stem form of *Nothofagus alpina* is as good as poplar (Tuley 1980). The other SRF species
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53 show a wide variation in stem form between individuals. Ash is sensitive to frost damage and
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55 this can result in poor stem form through death of the leader and so frost prone sites should be
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avoided (Dobrowolska et al 2011). Sycamore shows considerable variation in stem form (Hein et al 2009). Young alder often exhibits a straight stem with a compact pyramidal crown, but stem form becomes more variable as the trees age (Savill 2013). Stem form of *E. gunnii* is variable and often poor (Purse 2010, Marriage 1977), but improved material used in France exhibits good stem form (AFOCEL 2007).

Abiotic and biotic limitations

To be a productive tree for biomass, it must be well adapted to the abiotic and biotic environment. The following sections examine the limitations imposed on eucalypts and the other tree species identified by Hardcastle (2006).

Abiotic limitations

Most of the tree species in Hardcastle's (2006) list of potential SRF species are well adapted to climate of the UK and will grow well on a range of soil types. However, periods of low temperatures can be damaging to *Eucalyptus* spp. and *Nothofagus* spp. (Deans et al. 1992). Eucalypts are at the margins of their climatic limits in most of the UK: over the last decade there have been two winters (2009-2010 and 2010-2011), with extended periods of <-10°C overnight temperatures, causing widespread mortality to *E. gunnii* and *E. nitens* across a range of experimental sites planted in England (Harrison 2011) and in Scotland (McEvoy 2016). However, 2009-2010 was the coldest winter in thirty years and in some parts of England in 100 years (Prior and Kendon 2011) and 2010-2011 was only a little less severe (Met Office 2011). Furthermore, in a review of the impact of climate change on eucalypt plantations in general, Booth (2013) assessed their vulnerability as being moderate. He also noted that the short rotations often associated with eucalypts, compared with conventional forest rotations offered greater opportunities to change genotypes and silvicultural practices.

1 Murray et al. (1986) noted the high risk of *Nothofagus* being damaged: however, if southern
2 provenances are used and the hardiest individuals are selected, they are suitable for planting
3 in most lowland parts of the UK.
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8 Biotic limitations 9

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11 The risk of damage to trees from biotic agents is predicted to increase (Logan et al. 2003,
12 Sturrock et al. 2011) and is already having major impacts on forestry in the UK. European
13 larch (*Larix decidua*) is no longer planted due to the impact of *Phytophthora ramorum*
14 (Forestry Commission 2014), while planting of Corsican pine (*Pinus nigra* ssp. *laricio*) has
15 ceased because of damage from *Dothistroma septosporum* (Brown and Webber 2008).
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17 Wainhouse et al. (2016) provide useful predictions of those pests and pathogens likely to be
18 particularly damaging to trees in the UK in the future while another resource for appraising
19 the risk from insect pests and pathogens is the online UK Plant Health Risk Register (UK
20 Plant Health Risk Register no date). This does not provide a combined overall risk rating for
21 a tree species. However, the risk from pests and pathogens to Hardcastle's (2006) potential
22 SRF tree species can be broadly described as follows.
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40 There are tree species currently at high risk from damage, such as ash which is no longer
41 being planted due to the predicted damage from ash dieback (Woodward and Boa 2013).
42 Furthermore, an additional risk is that from Emerald ash borer (*Agrilus planipennis*), which is
43 now present in Russia (Straw et al. 2013), with the combined impacts likely to be severe
44 (Thomas 2016). Sycamore can suffer extreme damage by grey squirrels (*Sciurus*
45 *carolinensis*) and planting this species for timber is uneconomic in areas where high squirrel
46 populations are present (Savill 2013). For pathogens of sycamore, Webber et al. (2011) note
47 that *Phytophthora* spp and *Verticilium* wilt can be damaging in nurseries or newly planted
48 stock. *Cryptostroma corticale* also affects sycamore and remains dormant in the tree until it
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1 becomes stressed by prolonged dry conditions and the pathogen then causes an ailment
2 known as sooty bark disease, which results in crown dieback and can cause death of the tree
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4 (Savill 2013).
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8 Of the tree species there are those where potentially serious pests or pathogens are already
9 established in Britain. This group includes alder and *Nothofagus* which are at threat of
10 damage from *Phytophthora alni* (Gibbs et al. 1999) and *Phytophthora pseudosyringae* (Scanu
11 et al. 2012) respectively. This group also includes poplars, plantations of which have been
12 severely damaged by rusts (*Melampsora* spp) in the UK (Forestry Commission 2005).
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16 Damage by *P. alni* was first noted in Britain 1993 primarily infecting and killing the native
17 alder, but also grey alder (*A. incana*) and Italian alder (*Alnus cordata*) (Gibbs, et al. 1999).
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20 Other recent work (Černý et al. 2012) demonstrates that cold temperatures will kill the
21 pathogen and suggests that with predicted increases in winter temperatures due to climate
22 change, persistence of this pathogen may increase damage.
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26 Infection by *P. pseudosyringae* of *Nothofagus* was first noted in 2009 in a stand of *N. obliqua*
27 in Cornwall in the south of England, where in four plots between 50% and 72% of trees had
28 become infected. The susceptibility of *Nothofagus* to this disease prompted Scanu et al.
29 (2012 p27) to comment ‘A consequence of this damaging new disease is that future use of *N.*
30 *obliqua* and *N. alpina* in UK forestry as suitable species for climate change adaptation
31 strategies could be limited’. This view is supported by a recent review of *Nothofagus* in
32 Britain (Mason et al. 2018) which identified *N. obliqua* and *N. alpina* as having potential,
33 provided *P. pseudosyringae* does not prove to be highly damaging. Poplars are susceptible to
34 attack by rusts (*Melampsora* spp). Rusts cause premature leaf fall and can also disrupt
35 hardening in some hosts and other damage can include a reduction in growth, shoot die back
36 and when severe, tree death. Developing varieties of poplar resistant to rusts and to the
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highly damaging *Xanthomonas populi* that causes stem cankers is the main strategy to produce disease free stands. In the past, the Forestry Commission published a list of resistant varieties (Forestry Commission 2005) and a mix of resistant clones was planted to reduce risk further, however at present there are no fully rust resistant varieties available (Tabbush and Lonsdale 1999).

Birch is currently relatively free of major damaging biotic agents, although it is susceptible to attack by *Armillaria* (Webber et al. 2011). Furthermore, there have been problems of crown dieback reported in recent plantings of birch, in Scotland, due to three pathogens; *Anisogramma virgultorum*, *Marssonina betulae* and *Discula betulina* (Green 2005).

However, it is the threat from a pest, currently absent from the UK, that gives greatest cause for concern. The bronze birch borer (*Agrilus anxius*), if introduced would have a devastating impact (Nielsen et al. 2011) as silver birch and downy birch (*Betula pubescens*) are highly susceptible. Within 8 years of planting in a trial in the USA, all individuals of these birch species had been killed by the borer (Nielsen et al. 2011). The probability of detection of bronze birch borer in wood chips was extremely low using the current protocols in Europe (Okland et al. 2012), although the European and Mediterranean Plant Protection Organisations (2011) risk assessment suggested current measures meant the likelihood of bronze birch borer arriving in Britain is relatively low.

Finally there are the eucalypts which currently are probably at the lowest risk of damage from pests and diseases in the UK as few native pests of eucalypts have been introduced to plantations outside Australia (Fanning and Barrs 2013). The eucalypts identified as being suited to SRF in Britain are not those most susceptible to *Phytophthora* spp or to foliar pathogens (Webber et al. 2011). There are no records of major pest outbreaks in the UK, however there have been outbreaks of pests in Ireland. In the late 1990s a psyllid,

1 *Ctenarytaina eucalypti* was introduced to Ireland (Chauzat et al. 2002). Chemical control was
2 not particularly effective and so a parasitic wasp, *Psyllaephagus pilosus* was introduced and
3 this effectively controlled the psyllid (Chauzat et al. 2002). In 2007 a leaf beetle,
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5 *Paropsisterna selmani* caused severe defoliation in multi species plantings of eucalypts
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7 (Fanning and Barrs 2013, Horgan 2012). Fanning and Barrs (2013) describe the beetle as
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9 being a serious threat to eucalypts in Ireland, the UK and more widely in Europe as the adults
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11 are strong fliers, capable of surviving long periods without food and can tenaciously cling to
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13 various forestry residues.
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20 **Discussion**

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22 Eucalypts possess many of the silvicultural attributes that are attractive for SRF for biomass,
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24 namely rapid early growth, good stem form and methods for propagation and establishment
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26 that are well understood. This review of evidence supports the proposition that eucalypts
27
28 could provide a productive source of biomass in the UK and in other countries with oceanic
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30 climates in Europe. In Ireland, well-adapted species of eucalypts have been identified (Neilan
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32 and Thompson 2008) and spacing and other trials are underway (Tobin et al. 2016). In
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34 France there has been a programme establishing pulp plantations of cold-tolerant eucalypts
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36 that has been established for 35 years in the mid-Pyrennes. About 2,000 ha have been planted
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38 of *E. gunnii* and *Eucalypts x gundal*, its hybrid with *Eucalyptus dalrympleana* (FCBA 2018).
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46 The climate of the UK however is generally colder than Australia and the parts of France
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48 where cold-tolerant eucalypts are planted. Over most of the UK absolute minimum
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50 temperatures dip to below -14°C over a thirty year period (Figure 1), a temperature that will
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52 damage or kill most eucalypts, particularly young trees or when temperatures have dropped
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54 rapidly. It is mainly coastal or southern areas where absolute minimum temperatures remain
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56 higher (Met Office no date). Eucalypts are particularly vulnerable to cold damage because,
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1 unlike most temperate broadleaves they do not have a defined dormant period. Growth of the
2 naked buds begins above a certain minimum temperature threshold, which contributes to their
3 high productivity (Beadle et al. 1995). A study of *E. nitens* in Tasmania showed maximum
4 winter growth rates were only marginally less than those in summer (Davidson et al. 1995).
5 Hardening in cold-tolerant eucalypts usually commences below a temperature of between 2°C
6 (Paton 1983) and 4°C (Davidson and Reid 1987) and there are differences between species in
7 the rapidity of hardening and in the minimum temperature they will tolerate before damage.
8 Work by Black (no date) in Ireland developed an index of hardiness for eucalypt species in
9 Ireland based on lethal minimum temperature and rate of hardening and the index ranked
10 species tested in the following order, from most hardy to least hardy; *Eucalyptus rodwayi*, *E.*
11 *glaucescens*, *Eucalyptus subcrenulata*, *Eucalyptus delegatensis*, *E. gunnii*, *E. coccifera* and
12 *E. nitens*. This is a useful approach, although it raises questions as to why *E. gunnii*, a highly
13 cold-tolerant species ranked so low. Details of the provenance used was not provided and it
14 may be that a less cold-hardy one was used.

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35 The limited area of both *Eucalyptus* (Purse and Leslie 2016b) and *Nothofagus* (Mason et al.
36 2018) makes matching species to site imprecise but colder and more exposed sites must be
37 avoided. To identify climatically suitable sites for planting *Nothofagus* and *Eucalyptus*, Ray
38 and Sing (2006) created a map of England, Scotland and Wales that showed areas where
39 minimum temperatures of -14°C or below occur more than once every 50 years (Figure 1) as
40 a very broad indication of sites that had a low risk of cold damage (*cf.* Murray et al. 1986).

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An indication of relative cold of a site is currently not incorporated into Forest Research's
Ecological Site Classification (ESC) (Pyatt et al 2001) decision support system, a web-based
programme for matching species to site.

1 An important means of reducing risk is ensuring suitable species and provenances of
2 *Eucalyptus* are planted. Results from trials established in the 1980s (Evans 1986) or informal
3 planting (Purse and Leslie 2016a) have yielded useful information on species and
4 provenances that are well-adapted to parts of the UK. It is clear a wider range of eucalypts
5 could be planted (Purse and Leslie 2016a) than *E. gunnii* and *E. nitens* as proposed in
6 Hardcastle (2006) and incorporated into ESC. This has been recognised and the species most
7 planted in the UK between 2011 and 2015 was *Eucalyptus glaucescens* (Purse and Leslie
8 2016b). Table 4 describes recommended provenances for five promising eucalypts and the
9 areas of the UK where they are best suited. However, obtaining seed of superior provenances
10 has proven difficult and it is likely that sub-optimal origins have been planted in recent
11 decades in the UK.

12 The risk of damage by cold can be reduced further by focusing on species that readily
13 coppice as they are likely to recover from the main stem being killed by cold and thus
14 replanting costs can be avoided. Furthermore, coppice rotations are more productive than
15 first-rotations (Pukkala and Pohjonen 1990). A further approach to reduce damage is the use
16 of intensive silviculture to accelerate establishment and growth as larger trees are more
17 resistant to cold than smaller ones (Leslie et al. 2014a). Finally, to reduce the risk of
18 complete failure, plantations should comprise stands reflecting the full range of ages, from
19 those recently established to those of rotation age, as younger stands are more susceptible to
20 damage from cold.

21 A further positive influence on the suitability of eucalypts to the climate in the UK and other
22 temperate maritime environments is the likely effect of climate change on the frequency and
23 duration of extreme cold events. Climate models predict a reduction in the frequency of cold
24 events during winters in Western Europe, and in general a reduced severity (Peings et al.

2013). Gloning et al. (2013) predict warmer winter temperatures and no increase in the frequency of extreme winter temperature events for the UK. However, warmer springs may lead to greater frost damage; a study by Augspurger (2013) at a woodland in Illinois, USA described increased risks of frost damage to woody species over the last 100 or more years associated with an increased frequency of periods of warming in March followed by frosts in April. The species other than eucalypts listed by Hardcastle (2006) are pioneer species and so their phenology is influenced more by photoperiod and less by temperature (Basler and Körner 2012). It is likely that climate change will extend their growing season, but this will also increase the risk of frost damage (Basler and Körner 2012). A potential negative factor for eucalypts are increased levels of carbon dioxide. Heightened levels (twice ambient concentrations) of atmospheric carbon dioxide have been shown to increase susceptibility to frost damage through an increased ice nucleation temperature in cold-tolerant eucalypts, probably caused by bacteria on the leaves (Lutze et al. 1998).

The main constraints for using the wood from eucalypts as a source of biomass is the high moisture content and chemical composition of the wood. The high moisture content and requirement for some species for debarking for effective drying require additional inputs to produce a quality wood fuel. However, most of the plantations of woody energy crops in the UK have been SRC and wood from this source has as high a moisture content as eucalypt SRF. The high chlorine content of eucalypt wood creates acid gases and corrosion of boilers, however the concentration of chlorine can be considerably reduced (as much as 90%) by pre-heating the wood before burning through torrefaction (Kiepi et al. 2014).

If eucalypts were to be planted on a large scale in the UK, the environmental impacts would need to be quantified. The risk of invasiveness of *E. gunnii* and *E. nitens* is low. For both species, seed germination can be poor and the seedlings are susceptible to frost damage and,

1 for *E. gunnii*, it is also palatable to deer. Furthermore, for both species the small seed size
2 means that seedlings have few reserves and are vulnerable to competition from other plants;
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4 there are few UK sites where natural regeneration of *E. gunnii* has been observed and none
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6 where *E. nitens* has been recorded (GB Non Native Species Secretariat a & b). In general,
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8 Booth (2013) highlights the low risk of invasiveness of eucalypts in frost prone areas of the
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10 world. *Nothofagus* is also not considered to be a threat and is included in the exotic tree
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12 species where planting is not regulated under the Wildlife and Natural Environment Act of
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14 2011 (Forestry Commission Scotland 2015).
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20 There are limited studies on the effects of eucalypts on flora and fauna in the UK. Surveys of
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22 fungi showed that most of the mycorrhizal fungi associated with eucalyptus had originated
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24 from Australia, with a limited number of native British species (Pennington et al. 2011),
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26 although another survey identified rare fungal species, including three species representing
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28 three new genera to the UK (Hobart 2012). A study of earthworms under SRF and in
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30 comparison with pasture (Rajapaksha et al. 2013) suggested SRF should focus on native
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32 species but also *Eucalyptus* spp., which also supported dense populations of earthworms.
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34 Under the Great Britain Non-native Species Risk assessments (GB Non Native Species
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36 Secretariat no date a, & b), reviews were conducted of the environmental risk associated with
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38 *E. gunnii* and *E. nitens*. The conclusion of the analysis for both species was that they were
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40 both in the upper level of the 'low' risk category for environmental impact.
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47 In a review of predicted impacts of SRF on water quality and supply no problems were
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49 associated specifically with eucalypts, rather with intensively grown plantations (Nisbet et al.
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51 2011). Furthermore, evidence shows that eucalypts are very efficient at using water to
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53 produce biomass (Dvorak 2012).
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Conclusion

Eucalypts have many properties that make them attractive as a source of woody biomass in the UK. Where eucalypts have the greatest advantages is their potential growth rates that exceed those of the other species and are achieved over short rotations, although in practice high yields are often not achieved due to poor survival due to low temperatures. The risk of poor survival can however be mitigated by adopting four management approaches. The first is to focus on planting eucalypts that readily coppice as they are likely to recover from the main stem being killed by cold and thus replanting costs can be avoided. Furthermore, coppice rotations are more productive than first-rotations (Pukkala and Pohjonen 1990). A second means of reducing risk is the use of origins that have been proven to be best adapted to UK conditions. There is a growing body of information on the most suitable provenances for a limited range of eucalypts (Table 4). A third approach to reduce damage is the use of intensive silviculture to accelerate establishment and growth as larger trees are less damaged by cold than smaller ones (Leslie et al. 2014a). Finally, plantations should comprise stands reflecting the full range of ages, from those recently established to those of rotation age, as younger stands are more susceptible to damage from cold.

The high moisture content of green wood and the high chlorine content released during their combustion (Keipi et al. 2014) are constraints to the use of eucalypt wood as a fuel.

However, the moisture content is not higher than some other species, such as poplars (Table 3) and for SRC willow and methods have been devised for drying this material (Whittaker et al 2018). The problem of chlorine release on combustion can also be addressed through pretreatment by torrefaction (Keipi et al. 2014).

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Figure 1 Locations of sites with shaded area representing the -14°C minimum temperature monthly lowest (January) isotherm for (1961-90) (Met Office no date). The locations are as follows: (1) Moray, (2) Kilmichael, (3) Glenbranter, (4) Wark, (5) Daneshill, (6) Thetford, (7) Redmarley, (8) Exeter, (9) New Forest, (10) Chiddingfold.

Table 1 Characteristics of SRC and SRF (modified from SAC 2009)

	SRC	SRF
Production practices	Established at high planting densities using willow cuttings which are harvested every 2-4 years	Established from transplants at lower planting densities and harvested every 8-12 years
Inputs	Pre-planting herbicide. N application in year 2 after cutting. Few additional inputs	Pre-planting herbicide. N application to reflect crop uptake and maintain crop vigour. Few additional inputs
Yields	7-12 Mg (oven dried) ha ⁻¹ y ⁻¹	5-15 Mg (oven dried) ha ⁻¹ y ⁻¹ estimated – depending on species

Table 2 Attributes of the ideal SRF tree crop.

Silvicultural/ agronomic attributes	Wood property characteristics	Environmental characteristics
<ul style="list-style-type: none"> • Fast growth and high biomass yield (Guidi et al 2013), with mean annual increment (MAI) peaking early. • Resistant to pests and diseases and extremes in climate, such as cold and drought. • The ability to coppice (Dickman 2006, Hinchee et al 2009, Guidi et al 2013), or to sucker which avoids the costs of replanting and also enhances growth rates in the second and subsequent rotations (Dickman 2006, Hinchee et al 2009, Guidi et al 2013); • Produces straight stems; lowering harvesting, handling and transportation costs (Walker et al 2013); 	<ul style="list-style-type: none"> • Higher density wood in SRF species resulting in higher energy outputs per unit volume (Ramsay 2004) • Wood with a low moisture content and other characteristics that reduce the drying requirement (Senelwa and Simms 1999) • Wood with suitable chemical characteristics for combustion (Senelwa and Simms 1999), • Wood attractive to markets other than biomass, reducing market risk. 	<ul style="list-style-type: none"> • Low negative impacts on the environment, such as soil nutrients and moisture (Ranney and Mann 1994). • Reproductive or other characteristics that limit the likelihood of invasiveness (Gordon et al 2011) or hybridisation with native populations of trees (Felton et al 2013)

Table 3 Estimates of mean annual increment and biomass yield for potential SRF species (cf.Hardcastle 2006).

Species	Mean MMAI (m ³ ha ⁻¹ y ⁻¹) and range	Biomass yield Mg ha ⁻¹ y ⁻¹ (oven dried)	Specific gravity	Green Moisture content
<i>Eucalyptus nitens</i>	26 to 30 ⁷	N/A	0.45 ⁹ , 0.435 to 0.446 ²¹	56.2-59.3% ²¹
<i>Eucalypts gunnii</i>	16 ⁶	1.5 to 8.2 ⁵	0.50 ¹¹	-
<i>Nothofagus</i>	14 (10 to 18) ³	3.0 to 10.5 ⁵	0.6 ¹² , 0.45 to 0.53 ¹³	-
Poplar	9 (4 to 14) ¹	4.2 ⁵	0.36 ⁵ 0.335 ¹⁴ (aspen 0.48 ¹⁵)	64% ¹⁶ , 49- 56% ¹⁹
Sycamore	8 (4 to 12) ¹	0.6 to 5.7 ⁵	0.63 ⁸ (MC 12- 17%)	41% ¹⁶ , 48% ²²
Alder	4.5 to 14.6 ²	0.9 to 4.8 (red alder) ⁵	0.54 ¹⁰ (MC 12%), 0.43-0.49 ¹⁸	53% ²²
Birch	4 to 10 ⁴	0.5 to 5.7 ⁵	0.662 ¹⁷ , 0.53 ²⁰	43% ¹⁶
Ash	6 (2 to 10) ¹	0.5 to 4.7 ⁵	0.674 ¹¹	32% ¹⁷ , 40% ²³

¹Edwards and Christie (1981), ²Claessens et al (2010), ³Tuley (1980), ⁴Hynenen et al (2009),
⁵Kerr (2011) Table 16, ⁶Leslie et al. 2018, ⁷O'Reilly, Tobin and Farrelly (2014), ⁸Hein et al
(2009), ⁹Kibblewhite et al (2000), ¹⁰Claessens et al (2010), ¹¹AFOCEL(2004), ¹²Tuley
(1980), ¹³USDA (no date), ¹⁴Christersson (2010), ¹⁵Harrison (2009), ¹⁶Forestry Commission
(2011), ¹⁷Solid Fuel association no date. ¹⁸Milch et al (2015). ¹⁹Tharakan et al (2003),
²⁰Cameron (1996), ²¹Teagasc (2015), ²²Kent et al (2009).

Table 4 Recommended origins for selected eucalypts. Refer to Figure 1 for locations of sites.

Species	Recommended origin	Source	Notes
<i>E. delegatensis</i>	Var <i>tasmaniensis</i> from Ben Lomond, Tasmania	One of the more cold hardy origins in Evans (1986) and confirmed in Leslie et al (2014b).	Some mainland Australian origins are also hardy (Evans 1986). Recommended for warm areas of south west Britain with fast growth and good survival at a trial at Haldon Forest near Exeter. A valuable timber tree (FAO 1981).
<i>E. glaucescens</i>	Guthega, New South Wales	The most cold hardy of six origins in Evans (1986)	Adaptable to a range of sites and is unpalatable. One of the hardiest of eucalypts (Purse and Leslie (2016a)
<i>E. gunnii</i>	Lake MacKenzie, Tasmania.	One of the most cold hardy origins in Evans (1986) and confirmed Cope et al. (2008).	Performs well over a range of locations but variable growth; at 3 years of age trees at Exeter were twice the height of those at Chiddingfold, Thetford, Glenbranter or Wark. (Leslie et al. 2018)
<i>E. nitens</i>	Higher altitude provenances from Victoria.	Evans (1986)	Rapid growth but only to be planted in the least cold and least exposed sites.
<i>E. subcrenulata</i>	Mount Cattley, Tasmania	Evans (1986) recommended central or southern Tasmanian origins. Mount Cattley origin recommended in Leslie et al. (2014b)	To be planted in warm areas of south west Britain. Excellent survival and growth at a trial at Haldon Forest near Exeter (Leslie et al. 2014b).